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Practical Paper

Simple protocols for assessing dissolved air flotation systems: quantification of released air, bubble density and cloud patterns

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ABSTRACT

Dissolved air flotation (DAF) systems are useful for many water treatment applications. Optimizing a DAF system can be very difficult and complicated due to a multitude of variables that contribute to effective separation. Pressure, temperature, retention time and air mixing affect the ability of the saturator to increase air solubility, while baffle heights, flow rates and recycle ratios affect how the air that is released from solution interacts with the treated water. This paper focuses on two simple test protocols for quantifying dissolved air concentration in the recycle water and bubble density in the flotation tank. The primary purpose of this paper is to assist individual operators, technicians and engineers to develop their own protocols for their specific water and test conditions. A sample calculation is also included to illustrate the significance of these quantification protocols, which can be further modified as needed for a given set of parameters and variables.

Key words | air quantification, bubble density, dissolved air flotation, flotation tank, pressure saturation

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INTRODUCTION

Dissolved air flotation (DAF) is a water clarification process that removes suspended particulates by carrying the solids to the surface with microbubbles. The bubbles are formed by pressure saturation, which increases the solubility of air in water as described by Henry's Law. Higher pressures will provide greater solubility, but there is a diminishing return in pressures over 500 kPa (De Rijk *et al.* 1994). When the water is released from the dissolution tank and is exposed to atmospheric pressure, the air is released from saturation and forms tiny microbubbles with diameters ranging from 10 to 100 μm, with typical diameters of 40 μm (Edzwald 1995).

A traditional DAF system comprises two major components: the pressure saturator and flotation tank. The amount of air that will dissolve in solution is affected by pressure, temperature, hydraulic retention time and air mixing within the saturator. The flotation tank encourages contact between the saturated flow and untreated flow and is controlled by recycle ratios, baffle heights, flow rates and retention times. Lundh *et al.* (2000) and Han *et al.* (2007) describe the fluid dynamics of the particle–bubble collisions as having the greatest impact on removal efficiency in the flotation tank. Measuring how the variables of each of these parameters affect the performance of a DAF system is crucial for optimum treatment in terms of costs and water usage. The present paper focuses on the development of bench-scale test protocols for quantifying the released air, bubble densities and cloud patterns in a DAF system. Researchers can use the methods from this study to develop their own testing protocols, customized for their specific water and test conditions.

QUANTIFICATION OF DISSOLVED AIR IN WATER

Increasing the air dissolved in solution increases the energy efficiency by requiring less DAF recycle flow to treat the

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equivalent untreated flow (Ross *et al.* 2000). A better understanding of how the various parameters of the saturator affect air solubility can be obtained by quantifying the volume of bubbles produced. The total dissolved air mass leaving the saturator is not as important as the excess dissolved air mass beyond atmospheric saturation, as described by Haarhoff & Rykaart (1995). The amount of air that is released after depressurization can therefore be measured by a simple volume displacement system.

The body of the displacement system consisted of a clear 76.2 mm polyvinyl chloride (PVC) pipe that was capped on the bottom end and reduced at the top to a 12.7 mm national pipe thread (NPT) coupling with a reducer (Figure 1). The system was capable of holding a volume of over 1 L of water. A 12.7 mm NPT male with 15.9 mm barb was connected to a graduated 15.9 mm ID Tygon® tubing and was screwed into the top-reduced coupling. The Tygon tubing was marked up to 100 mL in increments of 10 mL. The left side of the top cap was tapped for accepting a 9.5 mm needle valve, which controlled the volume entering the quantification unit. The bottom cap was tapped with a 9.5 mm barb and 9.5 mm Tygon tubing was used as an outlet, which was extended to the height of the entire system. Raising the outlet tube to the height of the system prevented the drainage of the system when not in use. Steinbach & Haarhoff (1998) recommend using a similar system for measuring the precipitated air volume with a batch system; however, several adjustments were made for simplicity and to improve the accuracy. In this system, the inlet was moved higher and further away from the outlet. This prevented the need for a baffle and reduced the amount of bubbles that would be carried out with the exiting flow. The graduating tubing was also stopped at 100 mL as opposed to 500 mL; this allowed for more precise measurements of the precipitated air bubbles.

For every measurement taken, the following procedure was followed. With the inlet valve closed, the air quantification unit was filled with fresh water so that the water level of the outlet hose was level with the brim of the

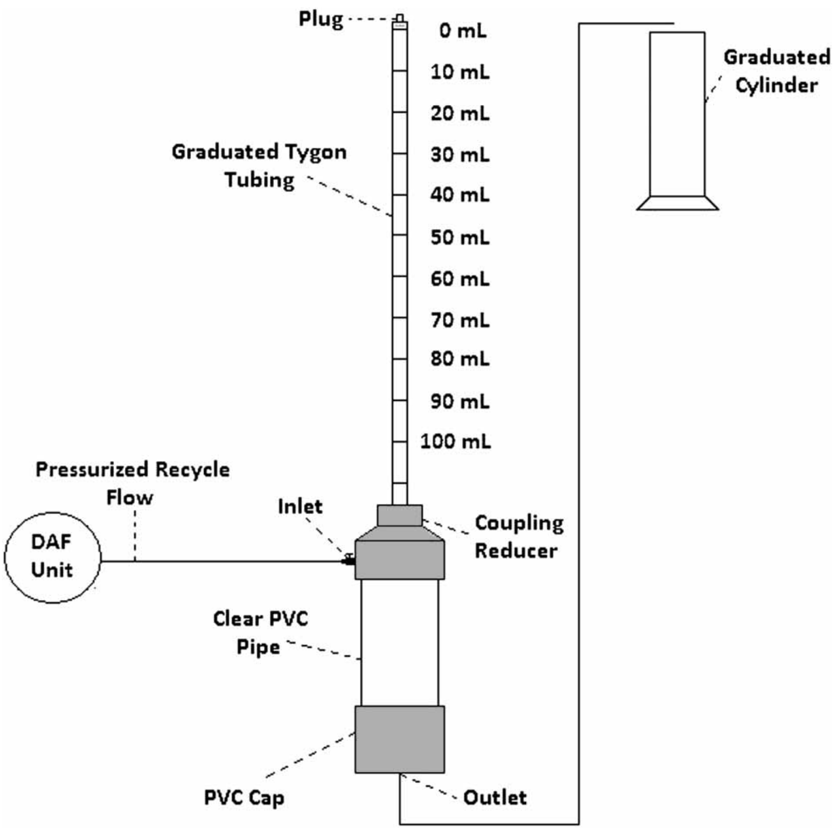

Figure 1 | An in-house-built air quantification unit was used to quantify the air released after depressurization. This unit can be effectively used for optimization of DAF treatment systems.

15.9 mm graduated Tgyon tubing. The 9.5 mm outlet Tygon tubing remained open to the atmosphere and emptied into a graduated cylinder. After filling the air quantification unit and the graduated Tygon tubing with water, the graduated tubing was plugged with a rubber stopper to prevent any air release. When ready, the inlet valve was opened to allow the air-saturated water from the DAF system into the measuring unit. The volume of water displaced by the incoming air and water exited the bottom of the unit and was measured in the graduated cylinder. When 1 L of water was collected, the DAF flow was turned off. During this time, air that was released from solution rose through the 15.9 mm graduated Tygon tubing where its total volume was measured. After waiting 5 min to ensure that all the air had been released from the solution, the outlet tube was lowered to the water level of the graduated tube and the plug was removed to equalize the pressure. This value corresponded to mL air released per L pressurized DAF flow.

QUANTIFICATION OF CLOUD HEIGHT AND BUBBLE DENSITY IN FLOTATION TANK

The flotation tank consists of two major areas separated by a baffle: the contact zone and flotation zone. In the contact zone, the air-saturated water entraps the particulates and contaminants from an untreated water source. Enough turbulence must exist here in order to provide adequate collision opportunities between bubbles and flocs (Leppinen *et al.* 2001; Lundh *et al.* 2002). When contact is made between bubbles and particulates, agglomerates are formed and carried over the baffle into the flotation zone, where they continue to the surface. Removal of these particulates depends on the volume covered by each bubble, the number concentration of bubbles and the capture efficiency as described by Sarrot *et al.* (2007). Increasing the contact between bubbles and particulates provides better clarification; higher bubble density is therefore desired.

Air solubility data alone may not always be enough to improve the separation effectiveness. For example, baffle location and size can alter the flow patterns and bubble cloud in a flotation tank drastically. Other adjustments such as increasing the hydraulic loading would result in the deepening of the bubble layer and change the air content in lower levels (Lundh *et al.* 2001). Currently, there is no established protocol for measuring bubble density in a flotation tank. This protocol is anticipated to allow researchers, engineers and DAF operators to estimate the bubble volumes at various locations in a flotation tank. For improved flotation designs and patterns, this protocol can be used on scaled-down prototypes with clear walls in any laboratory setting.

Measurement of the bubble density was achieved on a pilot-scale flotation tank with clear walls that allowed for visual observation. By using a grid that resembles a Secchi disk (Figure 2), the water clarity based on the concentration of bubbles was observed. The grid was made with 0.159 cm aluminum sheeting and was spray-painted with a 2.54 × 2.54 cm black-and-white pattern. The grid was placed in the flotation zone on the back wall of the tank (perpendicular to the baffles) and slid forward on a notch system that rested on the edge of the tank. For the present paper, clear water was used as the untreated flow and a percentage of that flow was the recycled air saturated flow. After the flow rates were adjusted and steady state had been reached, the grid was observed for a distinct black-and-white interface line or edge at every grid point. Each grid point (say A1) was defined as the point of intersection between the red line and the black-and-white interface line. If no distinct edge was detected, the grid was moved forward by a set distance on the top rail. This process was continued until each grid point became visible. Similar results were obtained when varying baffle height, recycle ratios and hydraulic retention times.

As indicated earlier, this paper was intended to provide researchers with a sample protocol that they could modify and use to effectively optimize their DAF systems. Bubble patterns for various wastewater systems with destabilized particles may be very different to those developed here with clear water. However, the procedure would not change if wastewater was to be used by the researchers.

Figure 3 depicts the photographs of the Secchi grid inside an acrylic flotation tank with various bubble flow patterns and densities. The hydraulic retention time was held at 20 min for all nine cases. The top row in this figure had a baffle height of 22.9 cm, the middle row 17.8 cm and the bottom row 12.7 cm. The first column used a 40% recycle

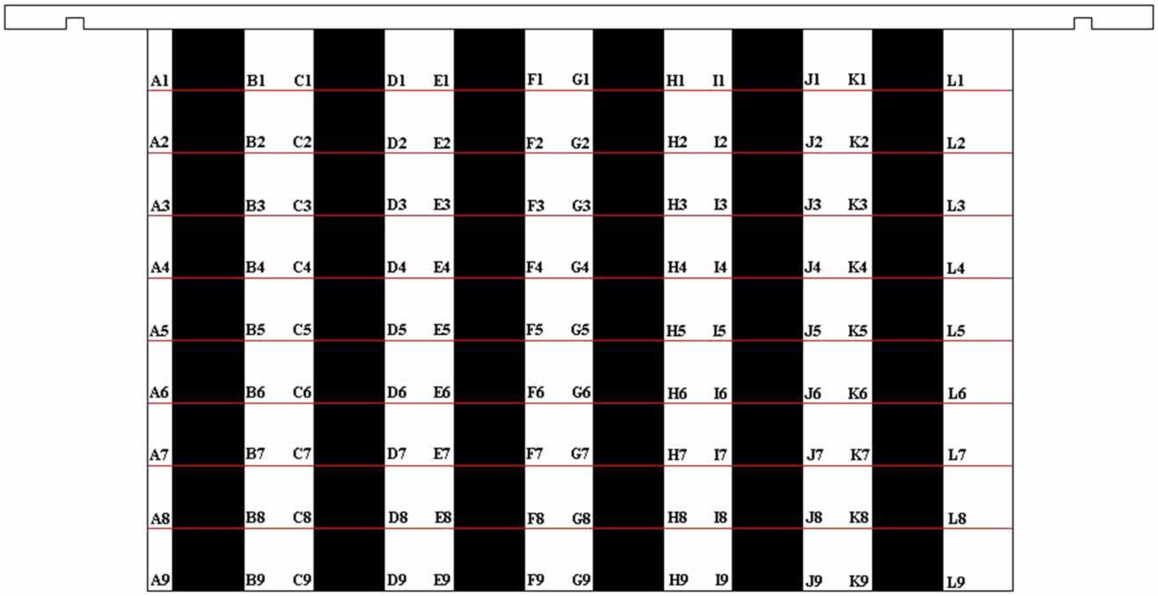

Figure 2 | A metal Secchi grid plate was designed and built for quantifying the bubble densities at various spatial locations in the flotation tank. The plate was placed in a flotation zone and slid forward and backward using the notch and rail system.

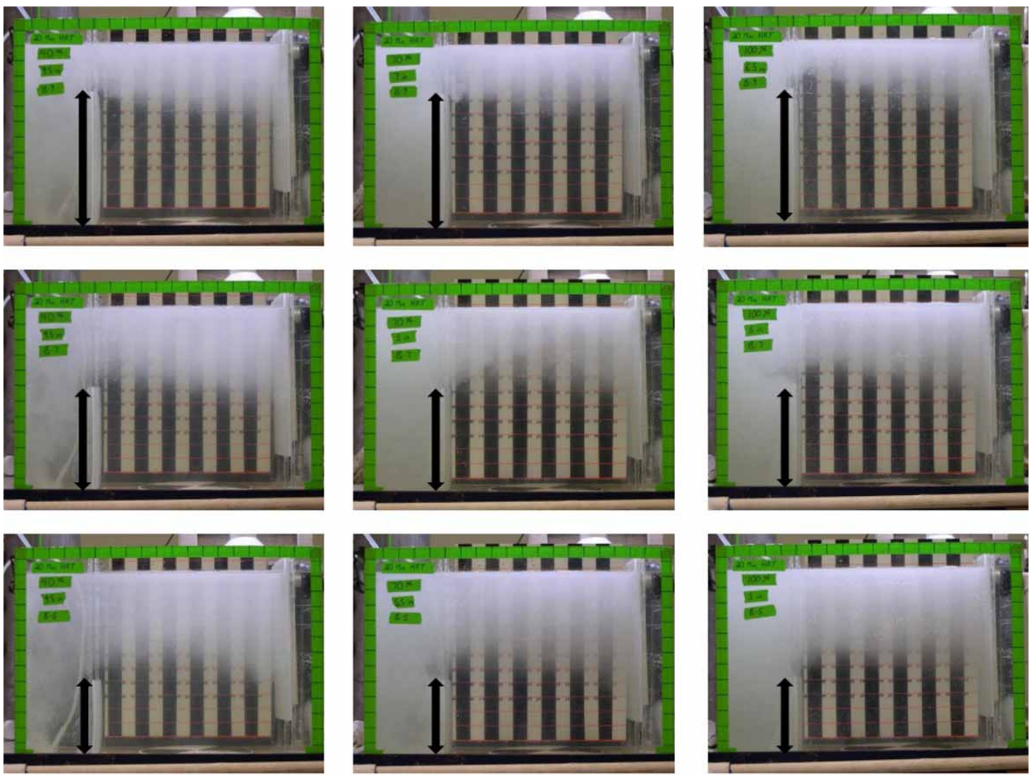

Figure 3 | Photographs depicting the bubble density patterns inside the flotation tank for various baffle heights and recycle ratios. The images were taken when the black-and-white edges of the grids were distinctly visible. The corresponding depths of the grids are listed in Table 1. The saturated flow was released to the left of the baffle at the bottom of the tank. Baffle heights are shown by superimposed double arrows.

Table 1 | Depths (cm) at which the black-and-white edges of the grids were distinctly visible

	40% recycle	70% recycle	100% recycle
22.9 cm baffle	24.1	17.8	16.5
17.8 cm baffle	24.1	12.7	12.7
12.7 cm baffle	24.1	14.0	12.7

ratio, the second column a 70% recycle ratio and the last column a 100% recycle ratio. Table 1 lists the distances measured from the front of the tank at which the edges of the black-and-white grids became distinctly visible.

From the nine cases, the centermost setting (70% recycle, 17.8 cm baffle height and 12.7 cm Secchi depth) was identified as the most effective choice as it provided the best bubble density with the smallest recycle ratio. It has to be noted that the visible bubble density in the centermost photo of Figure 3 alone cannot be used to make this judgment call. This is due to the fact that the respective photograph was taken at a much shorter Secchi depth than most other settings. A better understanding or overall picture can be obtained by considering the values in Table 1 together with respective flow patterns in Figure 3.

In this study, a long retention time (20 min) for the flotation tank was used and created a need for greater recycle ratios to provide a solid bubble layer. As described by Lundh *et al.* (2000), an increase in recycle rate with a following higher air content in the water results in a homogenizing of the flow, which became more stratified in character. Retention times less than 5 min are very common; however, that would increase the flow rates of both the saturated flow and untreated flow. Chung *et al.* (2000) determined an optimum surface loading rate of 7.5 m^3 $(m^2\ h)^{-1}$ which equated to approximately 2.5 min in hydraulic retention time. With a higher saturated flow (more dissolved air) the recycle percentage will decrease significantly and increase the system's efficiency by requiring less energy.

The Secchi grid depths were also used to estimate the bubble volume that existed in the flotation tank. A calibration curve was developed between Secchi depth and dissolved air volume. With a DAF system at steady state, developing such a calibration curve was fairly easy. Water was drawn from various grid points and the bubble volume was quantified using the set-up illustrated in Figure 1.

A sample calibration curve is depicted (Figure 4), mainly to show the trend. Note that calibration curves have to be developed for each individual DAF system because factors such as bubble size, water chemistry, water temperature and grid marking have a significant influence on the correlation between Secchi depth and bubble density.

The true power of the Secchi grid can be understood by quantifying the cloud patterns for various baffle locations/sizes or recycle ratios. Using the calibration curve and the following simple equation, we can compute the total amount of air or bubbles inside the flotation tank at steady state. Total air volume (TAV) in mL of air in the flotation tank at steady state is given by:

$$\mathrm{TAV} = \frac{\sum \mathrm{BD}_{IJ} A D}{1{,}000}$$

where BD_{IJ} is bubble density at different grid points in mL L^{-1}; A is area for each corresponding grid point in cm^2 (=6.452 cm^2 for our 2.54 cm grid); D is depth of water in cm (from front wall to back wall); and 1,000 is the conversion factor for cm^3 to L.

At steady-state conditions, it can be assumed that the particle removal effectiveness is linked to the total volume of air in the water column at a given time. Baffle designs or flow patterns that allow the bubbles to surface quickly will result in lower TAV. Researchers and design engineers can use these protocols or a modified version of these

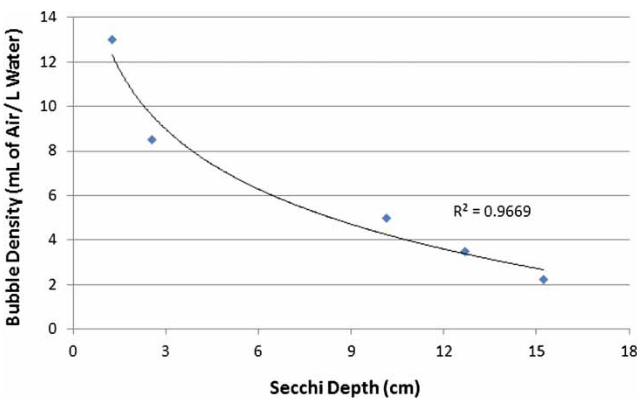

Figure 4 | Calibration between Secchi depth and bubble density generated using ambient air in freshwater at room temperature (c. 23 °C).

protocols to maximize the TAVs using scaled-down DAF prototypes with clear walls.

CONCLUSION

Air saturation and bubble stratification are two main factors that determine the treatment effectiveness of a DAF unit. Each of those factors has multiple variables which will alter how a system performs. The two quantification protocols described in this technical note provide tools to quantify air concentration in water and estimate the total volume of air within a flotation tank. These tools can be used directly or can be modified and used effectively to optimize a DAF system that will use smaller recycle ratios and be more cost effective.

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